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Hydrogeology of the Brunswick (Passaic) Formation and Implications for Ground Water Monitoring Practice

by Andrew Michalski

Abstract

Fractured shales of the Brunswick Formation provide a major aquifer in the most industrialized region of New Jersey. Numerous cases of ground water contamination have been documented in this formation. However, effectiveness of monitoring and remediation efforts is often hampered by the use of inappropriate concepts regarding ground water flow controls in this complex aquifer system. One such concept presumes that near-vertical fractures parallel to the strike of beds provide principal passages for the flow and produce an anisotropic response to pumping stress. Field evidence presented in this paper confirms that the Brunswick Formation hosts a gently dipping, multiunit, leaky aquifer system that consists of thin water-bearing units and thick intervening aquitards. The water-bearing units are associated with major bedding partings and/or intensely fractured seams. Layered heterogeneity of such a dipping multiunit aquifer system produces an anisotropic flow pattern with preferential flow along the strike of beds. Within the weathered zone, the permeability of the water-bearing units can be greatly reduced. The commonly used hydrogeologic model of the Brunswick as a one-aquifer system, sometimes with vaguely defined "shallow" and "deep" zones, often leads to the development of inadvertent cross-flows within monitoring wells. If undetected, cross-flows may promote contaminant spread into deeper units and impair the quality of hydrogeologic data. Hydrogeologic characterization of the Brunswick shales at any given site should be aimed primarily at identification of the major water-bearing and aquitard units. Recommended techniques for this characterization include fluid logging and other in-well tests.

Introduction

The Brunswick Formation is the thickest (about 10,000 feet) unit of the Newark Group (Kummel 1897) that crops out over a region stretching from southern New York state through northern and central New Jersey into eastern Pennsylvania (Figure 1). Throughout most of its outcrop, the Brunswick Formation provides a principal source of ground water. Numerous domestic, industrial, and municipal wells tap the formation with pumping rates ranging from a few to several hundred gallons per minute. In recent years, many of the water supply wells completed in highly industrialized and urbanized outcrop areas have been found to be contaminated and taken out of service. In the last decade, a dramatic increase in the number of monitoring wells installed in the Brunswick Formation has been observed.

The water-supply aspect of the Brunswick hydrogeology has been dealt with in a number of county-wide reports, which emphasize mostly statistical data on various types of water-supply wells. The issues of ground water distribution, movement, and potential contaminant migration pathways (which are important for proper design of ground water monitoring systems) have received little attention. Moreover, there appears to be a good deal of confusion on these issues in the published literature, which has occasionally led to improper monitoring practices.

Based on a review of the literature and field data from several sites in New Jersey, this paper attempts to reconcile often disparate concepts of ground water occurrence and flow in the Brunswick Formation. A more realistic conceptual flow model is proposed for the formation, together with guidelines for monitoring practices. Though this paper deals only with the Brunswick, much of its content may apply to other bedrock formations of the Newark Basin.

Concepts of Ground Water Occurrence and Movement in the Brunswick Formation

The Brunswick Formation consists of non-marine reddish-brown mudstone, shale, siltstone, and sandstone, which are interbedded with conglomeratic sandstones along basin margins. Three major basalt flows and diabase intrusions are present within a sequence of lenticular strata, which generally strike NE-SW and dip NW at 5 to 25 degrees (Figure 1). Locally, the strata are gently warped and broken by a few large faults and many small ones. Olsen (1980) named the thicker, Triassic (pre-basalt) portion of the Brunswick as the Passaic

Formation and further subdivided its post-basalt, Jurassic portion. Although the sites indicated in Figure 1 are located within the Passaic Formation, the older stratigraphic term is retained in this paper because terms like the Brunswick or Triassic "Aquifer" have an established use in the hydrogeologic literature.

Systematic fractures, both near-vertical joints and partings along the bedding, are generally believed to provide the principal passages for ground water flow through the Brunswick Formation. Even in conglomeratic lithofacies developed at the basin margins, the fracture permeability appears to dominate the bulk of formation permeability, despite sandstone matrix porosity values of up to 20 percent (Perlmutter 1959).

Ground water in the formation is said to occur under both water table and confined conditions. Rima (1955) identified the "unconfined" zone in the Lansdale (Pennsylvania) area, based on electric logs and flowmeter logs obtained while injecting water into selected wells. The low resistivity combined with a small but continuous decline in flow of injected water with depth was interpreted as indicative of higher water storage and lower permeability of this zone associated with weathered shales.

According to Rima (1955), the unconfined zone occurs to a maximum depth of about 250 feet, below which one or more artesian or semiartesian aquifers occurs to a maximum depth of about 600 feet. Where the bedrock is mantled by low-permeability drift or alluvium, a confined condition may exist at shallow depth in lowland bedrock areas (Gill and Vecchioli 1965, Nichols 1968, Nemickas 1969).

The notion of a multizone aquifer system within the Brunswick has generally been accepted by other researchers (e.g., Barksdale et al. 1958, Perlmutter 1959, Carswell 1976, Houghton 1986). Although the reported thickness of individual water-bearing zones has varied, it was considered rather small. Rima (1955) and Barksdale et al. (1958) estimated the thickness as generally less than 20 feet, while much smaller values (from a few inches to a few feet, with the average about 2 feet) were given by Longwill and Wood (1965) for beds in which secondary openings are well developed.

Differences in permeability between the layers, resulting either from variation in fracturing, weathering, or a combination of both, have been argued (Nichols 1968, Nemickas 1969) to account for the presence of the many water-bearing units and for substantial head differences often measured between the units (Perlmutter 1959, Carswell 1976). Because their relation to lithology is not clear, and strata are commonly lenticular, the individual water-bearing units have been difficult to define and to correlate. This has often led to a haphazard development of ground water supplies (e.g., Carswell 1976) and improper installation of monitoring systems (e.g., case described by Stothoff, 1990).

The directional, anisotropic response to pumping stresses is a well-documented feature of the Brunswick Formation in the region. In most cases, observation wells aligned along the strike of the formation react faster and show much greater drawdown than observation wells situated perpendicular to the strike (Herpers and Barksdale 1968, Vecchioli et al. 1969). However, some confusion exists as to possible causes of the observed anisotropic response of the formation. Is this behavior caused by an alignment of the principal set of near-vertical fractures subparallel to the strike? Is it that the observed anisotropic response is due to the fact that wells located perpendicular to the strike of a dipping set of heterogeneous strata may penetrate different aquifer zones than the pumped well? Or is it some combination of both causes?

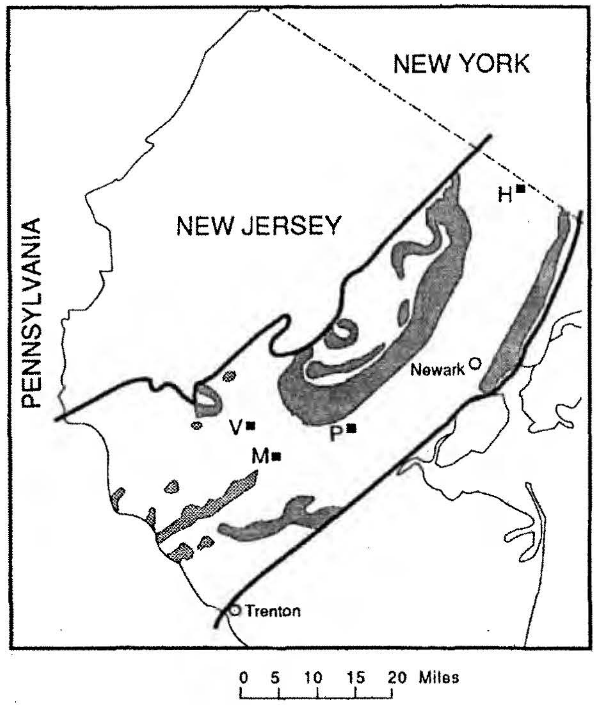

Figure 1. Map showing outcrop area of the Newark Group in New Jersey (between the heavy lines), igneous rocks (shaded areas), and locations of sites referenced in the text.

The first concept can be traced back to a paper by Herpers and Barksdale (1951) which discussed results of a pumping test in Newark, New Jersey. The authors argued that, with increasing depth, the weight of overlying materials would tend to close near-horizontal bedding fractures which tend to distribute water uniformly in all directions, while the near-vertical fractures would be less affected at depth, accentuating the tendency of water to flow in the direction of prevailing vertical cracks along the strike. They envisioned that individual vertical fractures might transmit water for distances of up to 2 or 3 miles without interruption, and that locally the fractures would extend to the top of bedrock, providing the hydraulic contact to the ground surface.

The concept that anisotropic behavior of the Brunswick strata is controlled by the alignment of vertical fractures along the strike of strata has been echoed in many later publications and reports (e.g., Vecchioli 1967, Nichols 1968, Spayd 1985).

On the other hand, there have been reports of substantial permeability variations in vertical profiles of wells, occurrences of discrete productive zones in association with bedding, and internal flows in wells in Pennsylvania (Rima 1955, Longwill and Wood 1965), southern New York state (Perlmutter 1959), and in New Jersey. At a site near Trenton, Vecchioli et al. (1969) documented the occurrence of ground water mainly in discrete zones controlled by bedding. The effect of tapping different producing zones on drawdowns measured during pumping was also evident at that site. Carswell (1976) characterized the ground water system in the Brunswick of northern New Jersey as consisting of a series of alternating tabular aquifers and aquicludes several tens of feet thick, which extended downdip for a few hundred feet and were continuous for thousands of feet along strike.

Field Evidence

Internal Aquifer Structure

Although any combination of the two presented concepts on control of fracture flow in the Brunswick shales can be envisioned, this author's data from a number of sites fit the latter concept. A conceptual model of the Brunswick Formation proposed herein embodies a "leaky," multiunit aquifer system, which consists of thin water-bearing units and much thicker, strata-bound, intervening aquitards. Both the water-bearing units and the aquitards are part of a homoclinal structure with a typical dip in the range of 5° to 25°. On the whole, such a structure is inherently anisotropic with the least permeability axis oriented perpendicular to bedding. The structure is capped by a weathered zone of lower permeability.

Figure 2 provides an example of the internal structure of the Brunswick Aquifer system at Site "P," where the formation is made up predominantly of mudstones. Three major discrete water-bearing units (designated on Figure 2 with letters A, B, and C) have been distinguished based on observations made during well drilling, temperature and electrical conductivity logging, in-well flow tracing, and slug testing. These major water-bearing units as well as several minor units are thin and separated by much thicker aquitards. In the construction of the cross section in Figure 2, information from some wells was projected over distances of several hundred feet (See map in Figure 2).

Despite such a distant projection, a consistent arrangement of the units parallel to the bedding is evident, implying a significant lateral extent for these major water-bearing units at Site P.

Ground water flow appears to be primarily influenced by partings along bedding and by the contrast in degree of fracturing.

Regarding their nature, the discrete water-bearing units in Figure 2 may represent larger bedding plane partings or seams of densely fractured rocks. The bedding partings provide a special class of fracture passages, not only because of their different origin, but also due to their consistent orientation and greater extent than any other fracture type. The greater extent of bedding discontinuities also tends to reinforce the effect of permeability anisotropy resulting from variations in fracturing and permeability between individual beds.

An earlier belief that bedding partings in the Brunswick play a minor hydraulic role because of their closure under increased vertical stress with depth (Herpers and Barksdale 1951) needs to be revised. The in situ stress distribution is often more complex than predicted from a simple model of gravitational stresses. The vertical stress at shallow depth may be less than horizontal stresses due to stress release in overconsolidated and partially eroded formations such as the Brunswick. Consequently, some bedding partings may become more open than vertical fractures. Besides, the flow within a bedding fissure should be visualized as occurring through channels meandering in between asperities that transmit load across the fissure walls.

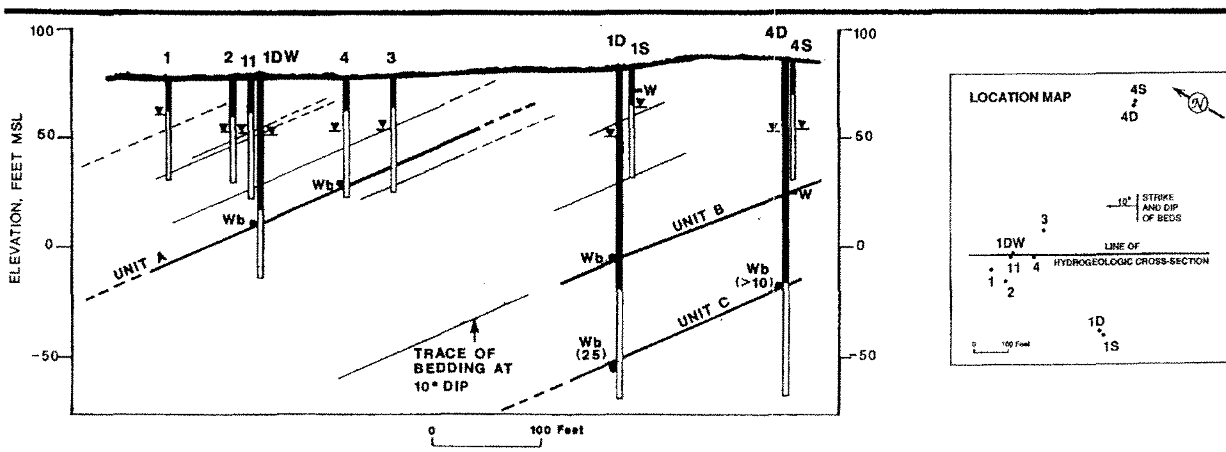

Figure 2. Hydrogeologic cross section and location map for Site P. Letter W at well bores indicates depth at which water was encountered during drilling by air-rotary method, Wb indicates water flowing from the hole, and number in parentheses gives flow-rate in gallons per minute.

Michalski and Klepp (1990) documented a case in northern New Jersey in which substantial flows occurred through discrete bedding partings in a sequence of predominantly thick sandstone beds of the Brunswick Formation. This site is designated as Site H on Figure 1. The significant role of bedding planes in controlling ground water flow is reported from other sedimentary basins (e.g., Trainer 1968).

Contrast in bed fracturing within the vertical profile of strata is the other major factor capable of producing discrete aquifer zones. Trends governing differential fracturing of beds need to be discussed. It has been known from fracture measurements in other sedimentary basins (e.g., Harris et al. 1960) and from theoretical considerations (Price 1966) that the frequency of systematic fractures/joints within individual units of a heterogeneous sequence is mostly controlled by the lithology ("competence") of each unit, its thickness, and the degree of tectonic deformation experienced by the sequence. A more competent bed tends to exhibit lower fracture frequency than a less competent one. For a given lithology and local tectonic history, the frequency should be inversely proportional to bed thickness (Price 1966).

Based on these rules, one can expect that thicker units of stiffer and stronger beds will exhibit fewer fractures than intervening thin beds of weaker lithologic types. In the case of the Brunswick sequence shown in Photo 1, fewer vertical fractures can be seen in thicker and more resistant mudstone beds than in shale seams. Conceivably, in such a sequence, the massive mudstone would act as an aquitard while the shale seams could furnish the production or water-bearing zones. The cyclic character of deposition of the Triassic formations (Van Houten 1969) has resulted in multiple repetitions of similar sequences at consistent intervals. The occurrence of multiple aquifer/aquitard sequences can thus be anticipated in these formations.

In addition to the most numerous, strata-bound fractures (to which the earlier discussion applies), several widely spaced, near-vertical fractures run across the sequence (Photo 1). These pervasive fractures impart a leaky character to the entire sequence. Due to the large apertures commonly found in these fractures, considerable leakage may be sustained at favorable in situ stress conditions in the absence of fracture infillings.

Distributions of Hydraulic Heads and Permeability

Apparent irregularities of the potentiometric surface are common at many monitored sites in the region. Water-level elevations in wells 1 and 1S on Figure 2 provide examples of such apparent anomalies; elevations observed in these wells are substantially higher than water-level elevations in nearby wells of similar

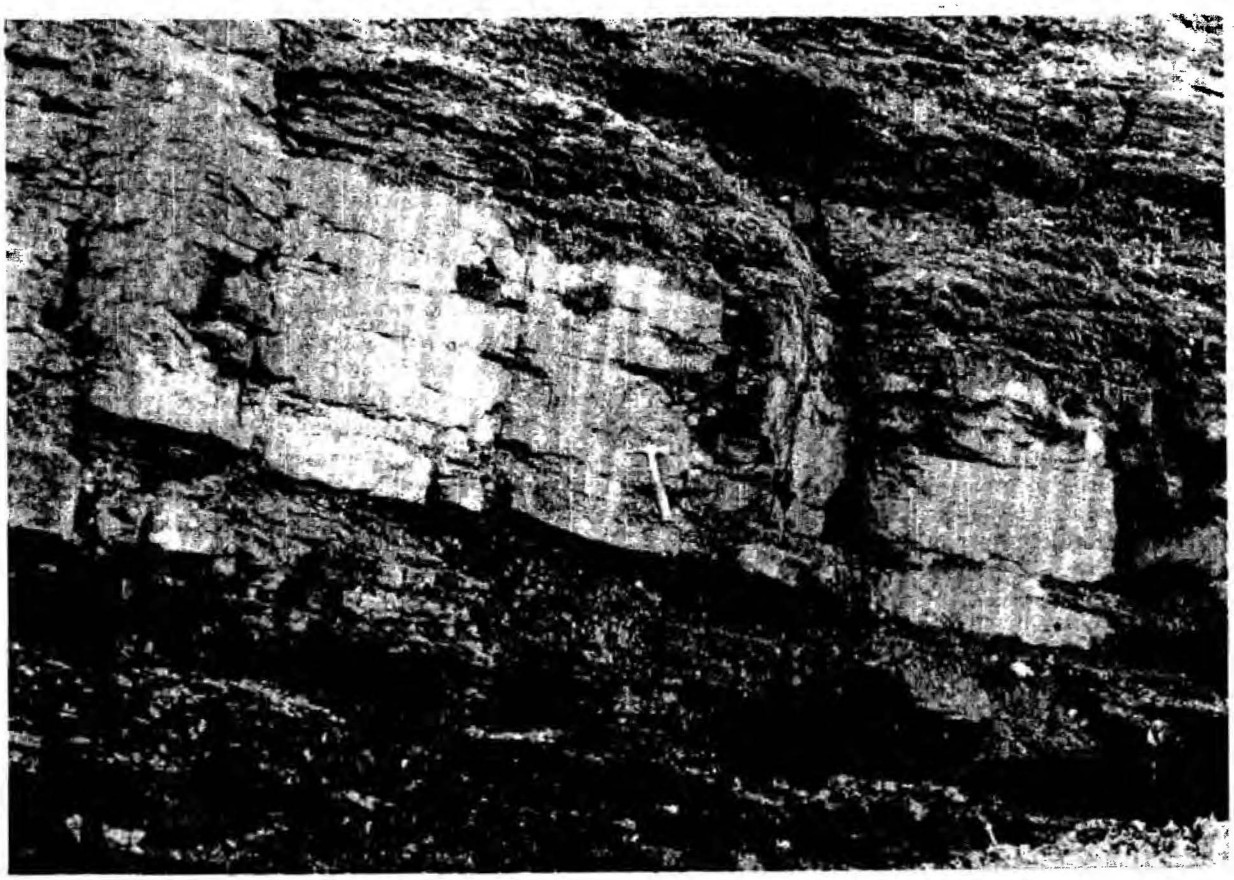

Photo 1. Fragment of exposure of partially weathered Brunswick Formation at Route 18 in New Brunswick, New Jersey. A thick mud-stone bed (indicated by the hammer and light color) shows few fractures, while intervening shales are densely fractured and water-bearing (dark color).

depth. In this particular case, the differences appear to result from positioning of open well intervals within different units of the formation. Wells 1 and 1S are open into aquitard units while other wells intersect intervening water-bearing units. Significant head differences can exist between individual units. Unless the structure of a multiunit aquifer is defined and the position of open well intervals with respect to the structure is accounted for, erroneous conclusions may be drawn from water-level data regarding the ground water flow direction and hydraulic gradients.

Wells in which significant cross-flows occur should be considered to be improperly installed.

Figure 3 shows a composite plot of depths to static water level vs. depth of wells for a total of 37 wells from three sites in the Brunswick Formation. A trend of an increasing depth to water level with increasing well depths is evident at sites M and V. This trend indicates the presence of strong downward gradients at both sites, which is a typical feature of recharge zones. The topography of sites M and V implies the occurrence of a recharging regime in the local shallow flow systems. The trend is not seen in wells installed at Site P, but a gentle topographic slope across the site and its position with respect to the nearest streams suggest that the site may be situated in a transition zone between recharging and discharging flow regimes.

In addition to the structure and topography, the observed distribution of hydraulic heads is largely influenced by weathering-related permeability changes with depth. In general, the weathering processes in shales result in the reduction of the primary fracture permeability by clogging the more conductive fractures with clay. The changes appear to be superimposed on the permeability variation inherent in the structure of multiunit bedrock aquifer system.

Figure 4 presents trends in distribution of the bulk hydraulic conductivity values (obtained from routine slug tests) vs. depth of open intervals in monitoring wells at two sites. The values obtained range over four orders of magnitude, from 10^{-6} to 10^{-2} cm/s. The lowest hydraulic conductivity values came from shallow wells that were completed within aquitard units, and higher values for shallow wells were associated with wells intersecting near-surface reaches of identified major water-bearing units (Figure 2). Wells open below a depth of 50 to 60 feet appear to intercept a transition from an intensely weathered shallow zone to an unweathered zone. Deep monitoring wells provided higher values of the bulk hydraulic conductivity and a lower variability of this parameter (Figure 4B).

Although weathering tends to reduce the permeability, numerous secondary fractures formed in the process

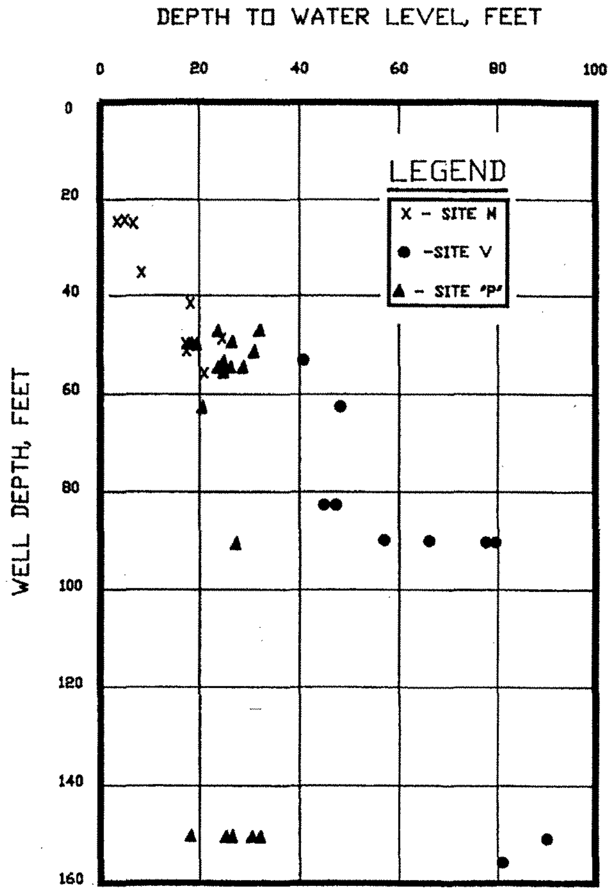

Figure 3. Relation of depth to water level with well depth for 37 monitoring wells at three sites in the Brunswick Formation.

may augment the storage potential of the weathered zone. As a result, pockets of perched water often form within and above the zone.

Preferential Flow in Undisturbed Aquifer System

The occurrence of a stratigraphy-controlled, multiunit aquifer system within the dipping bed setting tends to produce an anisotropic pattern of ground water flow.

In the saturated zone, primary flow is generally restricted to bedding fissures and fractured beds along strike. Usually, only minor deflections from that direction are attributable to the topography, flow boundaries and transient effects. However, the vertical flows may prevail across aquitards separating the aquifer units and in the weathered zone. These general principles can be useful in assessing the contaminant migration pathways within the Brunswick Formation provided that major aquifer and aquitard units beneath a site are located and sufficiently characterized.

Suggested Monitoring Practice

Contaminant investigations at sites located above the Brunswick Formation commonly involve installation of two sets of monitoring wells. The sets are usually referred to as the shallow and the deep wells, and are intended to monitor vaguely defined "shallow" and "deep" zones of the aquifer system.

The shallow wells are usually installed to span the first water-bearing zone noticed during installation of these wells. Completion depth of deep monitoring wells is sometimes determined by a typical depth of water-supply wells in the area. In other cases, the deep wells are drilled to an arbitrarily pre-selected depth (such as 100 or 150 feet). There is a tendency to complete all monitoring wells of a given set to a similar depth. Usually, the monitoring wells are 6-inch holes with open interval length ranging between 20 feet and several hundred feet.

The observed distribution of hydraulic heads is largely influenced by permeability changes.

Installation of 6-inch diameter wells in low-permeability portions of the Brunswick Formation can lead to significant errors in head measurements, which stems from large well storage and time lags in response to water-level changes in wells of larger diameters (Freeze and Cherry 1979). Time lags of up to two weeks were observed in some wells open to aquitard units and the weathered zone, while in wells open to major water-bearing zones the observed time lags were very short. Where permeability values obtained from wells at a site differ by four orders of magnitude (as depicted in Figure 4B), the variability of the response time among wells is yet another factor complicating interpretations of water-level measurements and pump-test data. Because the time lag is directly proportional to the square of the well radius, the use of smaller diameter holes is recommended for monitoring wells in the weathered zone.

The practice of well installation to an arbitrary target depth and of treating the Brunswick Formation as if it were one aquifer (or a two-zone aquifer) may be convenient for the design of ground water monitoring systems and for logistics of well drilling. However, the lack of consideration of the not-so-apparent internal structure of the aquifer system and of the 3-D nature of transport can bring about inadvertent detrimental side effects.

Of most concern is the chance of triggering cross-flows within open segments of wells caused by inadvertent bridging of aquifer units with different heads and/or transmissivities. Because of the trend of increasing hydraulic conductivity with depth of weathered zone (Figure 4), the chance of cross-flows is high for wells with longer intervals open across this zone, particularly for sites in recharge areas. If present, such cross-flows may affect or alter a pre-existing pattern of ground water flow, possibly inducing contaminant migration through the well into deeper bedrock units (e.g., Michalski and Klepp 1990). The potentiometric and chemical data obtained under such circumstances would be ambiguous, misguiding the development of remedial measures.

Wells in which significant cross-flows occur should be considered improperly installed monitoring wells. The use of short open intervals (generally less than 20 feet) helps to reduce the possibility of creating cross-flows. On the other hand, the placement of wells with shorter open intervals is not an easy task in situations in which a thick and apparently monotonous formation provides few clues on the location of potentially important water-bearing and aquitard units. Therefore, a trial-and-error approach to well placement in the Brunswick may be justified if inadvertent placement errors are rectified in a timely manner.

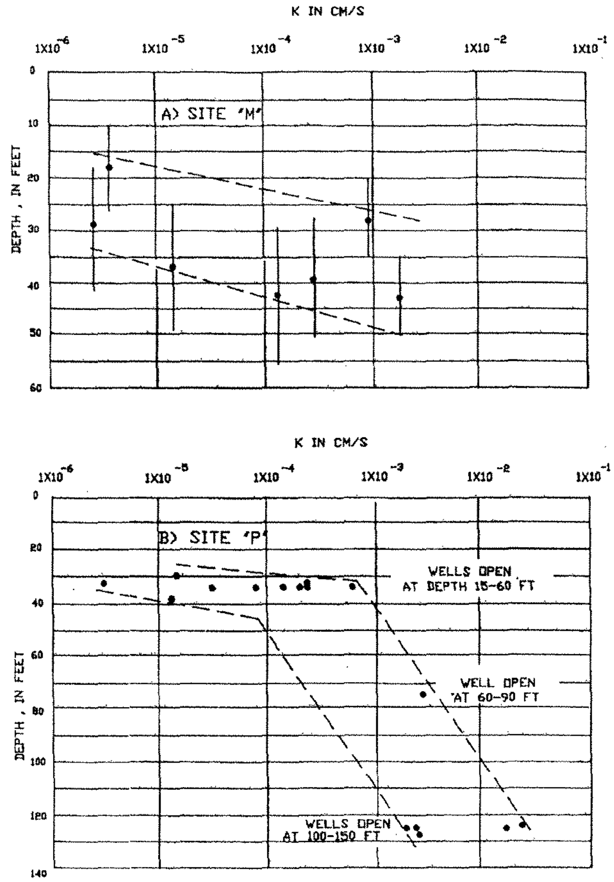

Figure 4. Distribution of vertically averaged hydraulic conductivity values vs. depth of open intervals of monitoring wells at sites M and P. Mid-points of open intervals are denoted by points, and vertical segments on the upper plot (Site M) represent the intervals.

To this end, there is a need to employ investigation techniques capable of locating major aquifer units and detecting internal leaks in wells. These techniques are outlined in following text. If a significant leak is detected in an existing well, such a well should be retrofitted to stop the leak. At new sites, pilot test wells may be drilled first, tested for internal leaks, and then retrofitted if needed. Retrofitting can be accomplished either by grouting a length of open interval from the well bottom, or by equipping the well with a permanent multipacker monitoring system. Cherry and Johnson (1982) and Black et al. (1987) provided descriptions of such multilevel systems. From the cost-effectiveness standpoint, the use of commercially available devices for multilevel

TABLE 1
Advantages and Limitations of Hydrogeologic Characterization Techniques Applicable to the Brunswick Formation

Technique	Information sought, advantages, and limitations
Surface Techniques	
Hydrogeologic Mapping	Bedrock lithology and structure, soil types, hydrologic features and flow boundaries. Less effective in the presence of thick soil mantle.
Test Pits/ Trenches	Thickness and character of soil/weathered zone, lithology, dip and strike of bedrock, orientation, spacing and character of fracture systems, presence of shallow water zones. Can be combined with soil sampling and the use of contaminant-sensing devices. Experienced geologist needed to obtain quality data.
Drilling Techniques	
Drilling/Logging and Well Installation	Air-rotary is preferred drilling method. Lithologic variations determined from cuttings and drilling rates ("hard" and "soft" zones). Position of major producing zones can be ascertained, and inflows associated with each zone can be estimated/measured. Wet zones above the standing water level can also be located.
Coring	Lithology and fracture characteristics can be evaluated, and formation samples can be taken for lab analysis. Some fractures can be induced by drilling. Generally expensive. Core recovery and quality dependent on geology and drillers performance, usually poor in fracture zones.
Intra-Well Techniques	
Downhole Video Survey	Fracture traces, apertures, and frequency, lithologic contacts, borehole wall profile, water seeps from fractures above the standing water level can be viewed in an open-hole TV survey. Watertightness of casing joints and grouting can be ascertained. Requires clean well water. (Acoustic televiewer was developed for mud-filled wells).
Temperature and Electrical Conductivity Logging	Locations of major transmissive fractures, possible vertical flows in a well, and water quality can be inferred from inflections of the logs. Qualitative. Inexpensive downhole probes are available and the logging is fast.
Other Geophysical Logs	Caliper, natural gamma, SP, and electric logs may provide information on lithology and in situ water quality. Specialized logging (such as acoustic wave form logging to infer fracture permeability) is still experimental.
Flowmeters	Velocity and vertical flows (either spontaneous or induced by pumping) within a well can be measured. Impeller-type meters stall at velocities less than 5 ft/min. More sensitive thermal flowmeters are not readily available.
In-Well Flow Tracing	Locations of transmissive fractures or fracture zones, occurrences of internal flows in wells, and relative hydraulic heads between the fractures or zones can be determined by repeated logging of electrical conductivity following an injection of a small-volume saline slug. Inexpensive and sensitive for slow flow velocities. Density effects may need to be considered.
Slug Testing	Vertically averaged hydraulic conductivity value (K) for the tested well segment can be obtained. Variability of (K) over the study area is quantified if tests are performed in many monitoring wells. Limited to settings with low and moderate permeability.

TABLE 1 (continued)
Advantages and Limitations of Hydrogeologic Characterization Techniques Applicable to the Brunswick Formation

Technique	Information sought, advantages, and limitations
Straddle Packer Testing	Injectivity/hydraulic conductivity for packed-off intervals, and conductivity profiles with depth. Test intervals are usually larger (at least 5 feet) than individual fracture zones.
Inter-Well Techniques	
Water Level/Potentiometric Surface Mapping	Distribution of heads, apparent flow direction and hydraulic gradient are usually determined from water-level measurements in monitoring wells. In multiunit aquifers, validity of such determinations depends on penetration of various units by individual wells. Apparent potentiometric anomalies can provide valuable information on the aquifer system.
Pumping Tests, Pulse Interference Tests	Typical objectives of these tests include determination of the degree of hydraulic connection between monitoring wells and aquifer/aquitard zones they penetrate, determination of apparent hydraulic parameters of the aquifer system or individual fracture zones, and demonstration of hydraulic control over a contaminated area.
Tracer Tests	Inter-well tracing under natural gradient is generally not feasible, but contaminants themselves can be viewed as tracers. Forced-gradient tracer tests can be performed in several configurations.

monitoring can be justified for larger projects.

Table 1 provides a survey of techniques of hydrogeologic characterization that may be used for the Brunswick Formation (and for similar settings with fracture-dominated permeability). For application in routine contamination investigations, only a few of these techniques are of interest.

Surface techniques, such as hydrogeologic mapping and test pits/trenches (Table 1), can be of considerable value in preliminary investigations. Because ground water occurrence and flow in the Brunswick are known to be strongly influenced by a homoclinal dip, lithologic variations, weathering, and hydrologic boundaries, knowledge of these characteristics at an early stage would aid in selecting locations for and placement of open intervals of monitoring wells. Air-rotary drilling is preferred as a well installation method, because it allows for observations and tentative identifications of major water-bearing zones. Downhole video surveys may offer a less expensive and often better alternative to coring.

In-well techniques, particularly those aimed at determination of intra-well fluid flow, are important tools for checking proper completion of individual monitoring wells, and for aiding in hydrogeologic characterization of the entire aquifer system. Temperature and electrical conductivity logging, flowmeter tests, and in-well flow tracing are included in this category (Table 1). These techniques are described by Keys (1989). The use of readily available electrical conductivity probes to track the movement and dilution of a small-volume saline slug injected into well makes a valuable and inexpensive testing method for monitoring wells installed in the Brunswick Formation (Carswell 1976, Michalski 1989, Michalski and Klepp 1990). Because of interpretation problems, routine pumping test analyses (Table 1) can be inadequate or misleading without a prior understanding of placement of the open intervals of pumping and observation wells with respect to the structure of a multiunit aquifer.

Conclusions

1. Ground water flow in the Brunswick Formation appears to be influenced primarily by partings along bedding and by the contrast in degree of fracturing between beds. A lingering belief that near-vertical fractures oriented parallel to the strike of beds dominate the flow is not supported by field data.
2. On a scale typical of most ground water contamination studies, the Brunswick Formation hosts a multiunit, leaky ground water system in which individual water-bearing units are relatively thin and parallel to the bedding. A large-scale anisotropic flow pattern results from inherent heterogeneity of the multiunit system. Along-strike flow direction is favored within the saturated reaches of individual water-bearing units, and vertical flow across intervening aquitards is produced by head differences in the water-bearing units.
3. Weathering of shales has further complicated the system by reducing the permeability of water-bearing units within the weathered zone and by increasing storage of the zone. Strong vertical gradients can

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develop across the weathered zone, particularly in recharge areas. This promotes the downward flow and contaminant migration through wells open across the zone and/or leaks developed behind casing. Special attention should be given to installation and testing of monitoring wells that intersect the weathered zone near known sources of contamination.

Differences in permeability have been argued to account for the substantial head differences.

4. Current practice of treating the Brunswick Formation as a one-aquifer system, sometimes with vaguely defined "shallow" and "deep" zones, often leads to the development of inadvertent cross-flows in monitoring wells. Undetected cross-flow may promote the spread of contamination through the wells, seriously impair the quality of hydrogeologic data obtained, and misguide the development of remedial measures.
5. Initial hydrogeologic characterization of the Brunswick Formation should be aimed at identification of the major water-bearing and aquitard units making up the aquifer system at a site. Fluid-movement measurements in existing wells or pilot holes, and other in-well testing techniques are feasible tools for such characterization.
6. In general, open intervals in monitoring wells should not exceed about 20 feet for the water-bearing units. Installation of wells open entirely to aquitard units should be avoided. The use of small-diameter holes is recommended for monitoring wells open to the weathered zone. For larger projects, the use of a multiple-packer monitoring system may offer a viable alternative to open holes.

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Biographical Sketch

Andrew Michalski is director of hydrogeology with Whitman Companies Inc. (385 Highway 18, East Brunswick, NJ 08816). He received an M.Sc. and Ph.D. in hydrogeology and engineering geology from Mining Academy in Cracow, Poland. He is a professional geologist and a certified ground water professional. Over the 20-year course of his career, he has worked on hot-water sulphur mining, radioactive waste isolation, hydrogeologic assessments, and aquifer cleanup projects at numerous sites. He was a senior hydrogeologist with TRC Environmental Consultants and The Earth Technology Corp., and has taught at universities in Poland, Nigeria, and at Rutgers University in New Jersey.